INTRA-MODULE DC-DC CONVERTER: TOPOLOGY SELECTION AND ANALYSIS

Urmimala Chatterjee, Johan Driesen
Katholieke Universiteit Leuven
ESAT-ELECTA, Kasteelpark Arenberg 10, 3001 Heverlee, Belgium
Email: urmimala.chatterjee@esat.kuleuven.be & johan.driesen@esat.kuleuven.be

ABSTRACT: In this paper, firstly the effect of partial shading on output power of a photovoltaic system is discussed and the limitations of a centralized power conversion for extenuation that problem is described. Here, the aim is to discuss the limitations of the state-of-art power conversion system and to analyze the possible solutions. The benefits of the distributed power conversion in terms of overall photovoltaic system efficiency are explored. This work presents the requirements of the intra-module converter in photovoltaic system and also discusses the different factors that need to consider while implementing a DC-DC converter as an intra-module converter. A topology of high gain DC-DC converter is presented here, which can be used in photovoltaic applications as an intra-module converter. This paper also demonstrates the suitability of this presented converter in photovoltaic applications. Simulation results of the proposed converter are also presented here.
Keywords: DC-DC converter, PV module, intra-module converter

1 INTRODUCTION AND MOTIVATION

Photovoltaic (PV) panels have long been argued to be a very attractive solution for future clean energy resource. The efficiency of a photovoltaic system is varied in different operating conditions by time-dependent effects. The efficiency of today's solar panel is about 18% to 23% [9] however the effective efficiency of a PV system is strongly affected by varying factors such as partial shading. In rooftop applications, these problems become more eminent. Because of the partial shading effect of the module, variations in output powers exist between different solar cells of the same PV module. These variations lead to a relatively significant power loss, which eventually affect the overall efficiency. The usage of centralized power converter for a large number of modules, make this power mismatching a crucial factor.

In state of the art research literature, only limited studies are available on the distributed power management techniques at the PV module level and especially at the string level. Due to the power mismatch occurs between different solar cells there is a significant power loss at the output. As a potential solution, distributed power management is preferred to be a key factor to improve the efficiency of the PV system. In order to minimize the power mismatches between different strings of solar cells, distributed converter can be integrated between strings.

In this paper, we discuss the difficulties of central power management and the benefits of distributed power management in PV system. Design requirements of an intra-module DC-DC converter for PV application have been reviewed and design specifications have also been set accordingly. A non-isolated high gain boost converter topology has been chosen [1] to implement as an intra-module DC-DC converter. Later sections include the description of the chosen topology and also explain the effectiveness of the proposed architecture [1] in this application. The converter is designed based on the chosen topology and then implemented in Spice to explore the performance and limitations it may impose. Conclusion of this paper is presented followed by the results of the converter.

2 SCIENTIFIC INNOVATION AND RELEVANCE

There have been limited approaches on the distributed power management proficiency. In state of the art research, most of the photovoltaic systems include a panel of multiple modules, in series or in parallel, connected with a central DC-AC inverter through a central DC-DC converter. Central inverters are mostly used for large scale PV applications where shading or different orientation of modules is prevented from the planning stage and the impact of them is negligible [7]. However, the central power converters are not able to deal with the problems of power mismatch between the cells as well as between the modules. In case of central inverter, the MPP tracking is done centrally and the mismatch losses of the strings of the module result to high energy losses of the system [8]. In order to mitigate this mismatch problem, some of the literature focuses on the module level DC-DC conversion as a possible solution [2] that decreases the impact of mismatches by performing MPP tracking at module level. In a previous attempt [3], the benefits of module level converter have been identified and discussed in detail about the module level DC-DC conversion. It has been proposed a concept of ‘delta conversion’ for module level converter to average out differences in output power between groups of PV cells within modules and between modules inside the PV system [3]. In [10], one asymmetrical boost converter topology has been presented for PV application. To achieve high gain more inductive elements have been used in this topology, which is a constrain to build a compact converter and accordingly for an intra-module PV converter. Some of the approaches in the literature deal with mismatch problems within the module and can be used at sub-module level power conversion [4].

In this work, the affect of partial shading on overall PV system efficiency is explained and as a potential solution distributed power conversion system is proposed. The benefits of distributed power conversion over centralized power conversion in photovoltaic system are discussed. A non-isolated high gain DC-DC boost converter topology is chosen [1] for this application. Later sections include the description of the chosen topology and explain the suitability of that topology as a low power high frequency intra-module DC-DC converter. The converter is designed and implemented in Spice to explore the performance and limitations it may impose. Conclusion of this paper is presented followed by the results of the converter.

3 APPROACH: INTRA-MODULE POWER CONVERSION

3.1 Power mismatch

In general the solar cells and the modules can be either connected in series or in parallel in a PV system. A number of cells can be connected in a series string to increase the voltage level or in parallel to increase the current level or in a combination of the two to form a PV module. Several modules are also connected in similar fashion to produce large PV power. Because of the partial shading different cells in a single PV module generate different power. There are power mismatches between these interconnected cells and also between interconnected modules due to their non-identical properties and the different operating conditions. Mismatch effects may occur either in the short-circuit current among series connected cells or in the open-circuit voltage among parallel connected cells. Because of the partial shading, cells are illuminated with different irradiance level and so each of them has different current-voltage characteristics. The current available in a series connection of solar cells is limited by the current of the solar cell that is less illuminated. When solar cells of a module are in series and module is partially shaded then the excess current produced by the most illuminated cells are in forward biased and causing the reverse bias of the least illuminated cells. This may result in power dissipation in the cells instead of power generation and consequently, will affect the overall efficiency. This effect is known as short-circuit current mismatch. Moreover, this current mismatch effect can also cause large power dissipation on the least illuminated cells which leads to a phenomenon called hot-spot heating and which may damage that cell permanently. In case of parallel connection among the strings, open-circuit voltage mismatch leads to a lower total operating voltage and a significant power loss.

3.2 Limitations of central power conversion

In state of the art work, the most common topology of the interconnection between the solar modules and the grid is by using the central inverter. Many cells are connected in series to form a module and these modules are connected in series or parallel in order to achieve high voltage and multiple modules are connected to the input of a single DC-AC inverter through a single DC-DC converter. Traditionally bypass diodes are connected between the strings of the module to prevent from the mismatch effect as shown in figure 1 [11]. These diodes are connected in parallel, but with opposite polarity, between the string of solar cells. When partial shading occurs, if one cell is shaded the complete string is used to be bypassed by using bypass diode, although the other non-shaded cells in the string are perfectly able to deliver power. That way the generated power by the non-shaded cells is lost. It entails that even a small area of the module is shaded, may lead to a significant power drop. The efficiency of the PV system is decreased by using the central converter especially for low power application because the problem of partial shading and of the power mismatching on the module level becomes more eminent in case of low power application. As it is explained, the power level of strings of the module should be matched and operated under the same conditions because of the series connection of cells within the string. This limitation makes the central converter configuration unattractive.

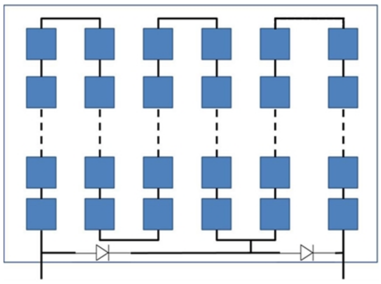

Figure 1: Two bypass diodes are connected between strings in a module

3.3 General approach of distributed power conversion

In order to limit the effects of mismatch effect, the approach of distributed power conversion is introduced, where more than one converter are used between several modules. In the literature, different topologies for distributed power conversion for PV system have been proposed. Some of the approaches are based on module level solution such as module integrated DC-DC converter [2] that minimizes the impact of power mismatches by performing MPP tracking at module level. However, mismatches between strings inside the module cannot be mitigated by using module level DC-DC converter. Hence, we propose to implement an intra-module DC-DC converter at string level so that every string has its own MPP tracking. One of the approaches of using intra-module DC-DC converter in a PV module is depicted in figure 2 [12]. Here in a PV string, the cells are connected with converters in series to build up the power and strings are connected in parallel with each other through their corresponding converter. These intra-module converters will be in operation dynamically based on illumination condition. When the entire module is fully illuminated and no mismatches are present within strings then one converter will be operational for the whole module and rest two converters will be shut down. So, the reliability as a whole of the module will be increased because all the converters will not be in operation all the time. By using these converters, overall efficiency of the PV system will be improved since the generated power by the partially shaded cells will also be added in total power instead of killing the whole string by using bypass diode. Number of intra-module converters in a module and the connection of these converters with each other and also with the string will be varied depending on the requirement.

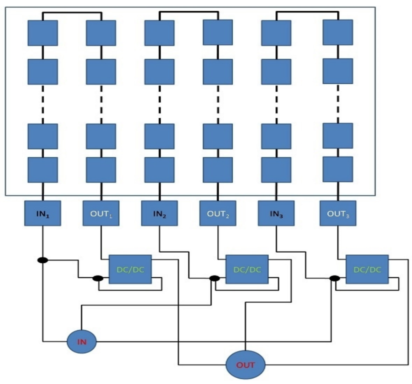

Figure 2: Three strings of cells in series connected with

local DC-DC converters in parallel connection

4 TOPOLOGY SELECTION FOR INTRA-MODULE CONVERTER AND SPECIFICATIONS

4.1 Design Requirements and topology selection

Based on the effectiveness of the intra-module DC-DC power conversion following design requirements are defined. In order to address low voltage output from PV cells in shading conditions, the converter should work with minimum input voltage of around 10V, i.e. at least 20 cells should be connected in series. The maximum input voltage of the converter is set to be around 30V that is the operating point of the module when no shading and thus no mismatches are present within stings. So, wide input voltage range needs to be selected to operate the converters dynamically, depending on the mismatches present. Output voltage of these converters should be high enough so that minimum stages of power conversion will be needed before interface with the DC-AC inverter. So, it is important to have high voltage gain to achieve high output voltage of the converter. Since intra-module converter needs to be compact and small size to be implemented at string level, a high frequency transformer-less converter is required. Non-isolated converter needs to be selected to make small size and cost effective converter. Higher frequency design allows for decreasing the magnitude of passive values and in turns, the corresponding physical size of the passive components. Smaller values components reduce the energy storage in the circuit, allowing for the improved transient response. High operating frequency will be also beneficial to reduce ripple current. Since generated power from the string of the module is not high enough, low power converter is required to interface the converters at string level inside the PV module. Ripple current should be as low as possible because high ripple can causes MPPT fluctuation. High efficiency of the converter is also an important criterion, which will help to improve overall system efficiency.

4.2 Suitability of the topology

For this application classical boost converter is not a good option, because this converter requires a very high duty cycle to achieve high gain and a very high duty cycle can increase the voltage stress across the power switches. Therefore, it is recommended to use alternative topologies that do not need very high duty cycle. In literature, there are different kinds of topology which can be used as an intra-module converter. A boost-flyback converter integrated with high static gain is proposed in [5, 6]. For these converters, voltage stress across the switches is lower than half of the output voltage which leads to lower conduction loss and eventually, high efficiency. However, it has a pulsating input current which can increase input ripple in the circuit.

A non-isolated interleaved boost topology [1] has been chosen to design a low power, high gain, high frequency DC-DC converter for intra-module power conversion. The schematic diagram of the topology is shown in figure 3 [1]. In this topology, multiplier capacitors are connected in series and integrated in boost converter with the possibility to increase several stages to achieve high gain. Two multiplier capacitors are connected with two multiplier diodes to form a multiplier stage (M). In this figure, two multiplier capacitors (CM1, CM2) with two multiplier diodes (DM1, DM2) are connected to form first stage of multiplier circuit and hence multiplier stage (M) is one here. The diodes DS1 and DS2 are the output diodes. These multiplier diodes help to charge the multiplier capacitors with a voltage (V_M) which is actually the output voltage of the classical boost converter. The output voltage of the circuit is equal to the (M+1) times the voltage V_M for this topology. Therefore, the voltage gain of this circuit is the function of the number of multiplier stages (M) and that way, by increasing the multiplier stages, is possible to achieve high voltage gain without high voltage stress. Since two power switches (S1 and S2) are connected in parallel, the voltage stress across the switches is limited to half of the output voltage, resulting in lower conduction loss, which in turn helps to increase efficiency. The current is divided among the various multiplier diodes, as in parallel connection and this also helps to reduce conduction losses of the diodes. Because of the configuration of the switches, it is possible to implement interleaved switching technique. Due to the interleaved technique, low input current ripple and low output voltage ripple can be achieved. This technique also helps to reduce current stress in all components. To minimize ripple of the circuit and to make a compact converter high switching frequency is defined. Switching frequency for this design is fixed at 500 kHz. The duty ratio of the converter will be varied to operate the converter at wide input voltage range and at fixed output voltage. This topology is suitable to operate in higher and lower than 0.5 duty ratio. As low power converter is required to interface at string level, the designed converter is rated lower than 300W. The multiple usages of diodes may introduce power loss because of their reverse recovery current, which can be overcome by using low loss diode such as SiC diode or by adding some extra circuit such as snubber circuit. Table 1 shows the design specifications what we have defined for the intra-module converter.

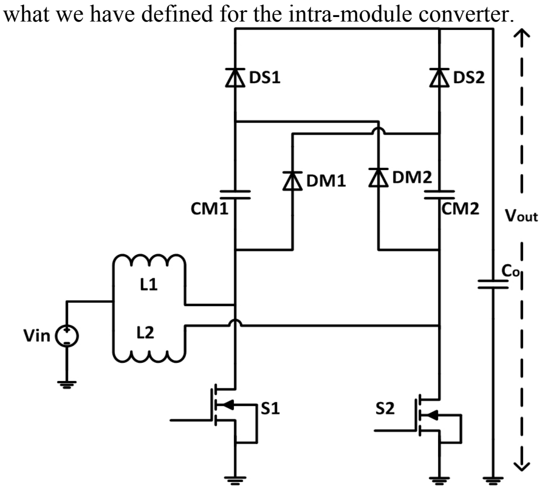

Figure 3: Chosen topology for intra-module converter

Table I: Design specifications for the converter

Design Specifications	Values
Input voltage range (V)	10-30
Power range (W)	80-240
Max. input current (A)	8
Operating frequency(kHz)	500
Output voltage (V)	120
Max. voltage gain	12
Avg. Efficiency (Min.)	95%

5 RESULTS AND DISCUSSION

The chosen topology is designed and implemented in Spice to explore the suitability of this topology as intra-module converter. Real commercial model of MOSFETs and diodes have been used for all these simulation. In this application, the designed converter is simulated with M=2, operating in continuous conduction mode. The static gain (A_v) of the converter is shown in equation below, where M is the number of multiplier stages and D is duty ratio of the converter.

$$A_v = \frac{\mathrm{M}+1}{1-D}$$

Figure 4 presents the converter operational waveform (simulated) when M=2 and D=0.75 and shows that this topology can be used to achieve gain of 12. It is also shown that the converter is able to respond with wide input voltage range between 10V and 30V. Here the input voltage is simulated with minimum of 10V to maximum of 30V in steps of 5V.

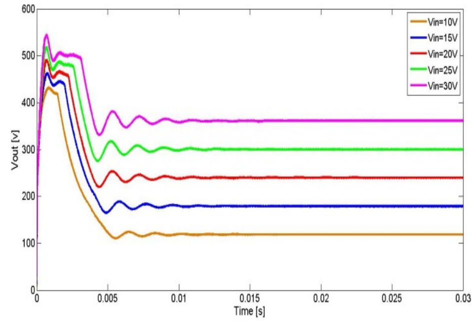

Figure 4: Output voltage with varying input voltage from 10V to 30V with 5V step

The designed converter is simulated with switching frequency of 500 kHz when M=2 and D=0.75. Current waveforms of this simulation are depicted in figure 5 and it is also shown the interleaved operation of the two inductor's current. The input current is considered as 8A. The switching signal for the two MOSFETs (VS1, VS2), current of two inductors (I(L1), I(L2)) and current of two output diodes (I(DS1), I(DS2)) are shown here. According to the theoretical waveform [1], the simulated current waveforms of the converter give an expected result of the topology, working at 500 KHz. This demonstrates the viability of the selected topology at high frequency operation.

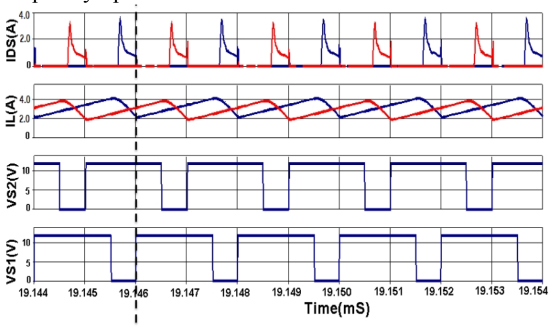

Figure 5: Current waveform of inductor current and output diodes current of the converter at 500 kHz frequency. Black dotted line indicates one switching cycle

The input ripple current is reduced by using high switching frequency (500 kHz) and due to the implemented interleaved technique. In this case, ripple current is approximately 9.1%, which is shown in figure 6.

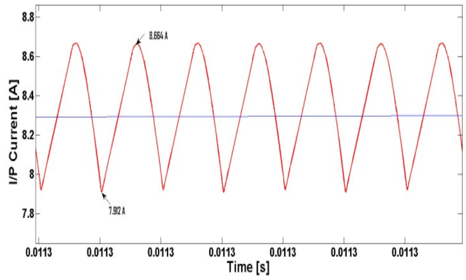

Figure 6: Waveform of input ripple current. This ripple is 9.1%

6 CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

From our work, it is concluded that intra-module converter is beneficial in terms of overall performance improvement of the PV system. It is also seen that this topology is suitable to operate at high frequency and useful to achieve high voltage gain of a converter. It is also possible to attain significant low input ripple current due to implemented interleaved technique and for the very high switching frequency operation. Therefore, the designed converter is very appropriate to use it as a distributed DC-DC converter at string level of the PV module.

6.2 Future work

A fully-working prototype of this converter will be built and extensive measurements will be done to verify the simulation results. Microcontroller based control system will also be designed to control the duty ratio of the converter.

7 ACKNOWLEDGEMENTS

This work is supported by the 'SMART PV' project under IWT-SBO grant. This work also acknowledges the help of Alex and power electronics team in ESAT-ELECTA in KU Leuven.

8 REFERENCES

[1] M. Prudente, L. L. Pfitscher, G. Emmendoerfer, E. F. Romaneli, and R. Gules, "Voltage Multiplier Cells Applied to Non-Isolated DC-DC Converter", IEEE Transactions on Power Electronics, Vol. 23, pp. 871-887.

[2] L. Linares, R.W. Erickson, S. MacAlpine, and M. Brandemuehl, "Improved Energy Capture in Series String Photovoltaics via Smart Distributed Power Electronics", 24th APEC, 2009, pp.904-910.

[3] H. J. Bergveld, D. Büthker, C. Castello, T.S. Doom, A. de Jong, R. van Otten, and K. de Waal, "Module-level DC/DC Conversion for Photovoltaic Systems", Telecommunications Energy Conference (INTELEC), IEEE 33rd International, 2011.

[4] C. Olalla, M. Rodríguez, D. Clement, J. Wang, and

D. Maksimović, “Architecture and Control of PV Modules with Submodule Integrated Converters”, Control and Modeling for Power Electronics (COMPEL), IEEE 13th Workshop, 2012.

[5] K. C. Tseng, and T. J. Liang, “Novel high-efficiency step-up converter”, IEE proceedings on Electric Power Applications, vol. 151, pp. 182-190, Mar. 2004.

[6] T. J. Liang, and K. C. Tseng, “Analysis of integrated boost-flyback step-up converter”, IEE proceedings on Electric Power Applications, vol. 152, pp. 217-225, Mar. 2005.

[7] F. Blaabjerg, R. Teodorescu, Z. Chen, and M. Liserre, “Power converters and control of renewable energy systems”, IEE proceedings on Electric Power Applications, vol. 152, pp. 217-225, Mar. 2005.

[8] S. B. Kjaer, J. Pedersen, and F. Blaabjerg, “A review of single phase grid connected inverters for photovoltaic modules”, IEEE Transactions on Industry Applications, Vol. 41, No. 5, 2005.

[9] M. A. Green, K. Emery, Y. Hishikawa, and W. Warta, “Solar cell efficiency tables (version 37)”, Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.1088.

[10] E. I. A. Zuluaga, C. A. Ramos-Paja, and A. J. Saavedra-Montes, “Design of asymmetrical boost converters based on photovoltaic systems requirements” , Dyna, year 79, Nro. 171, pp. 31-40. Medellin, february, 2012.

[11] U. Chatterjee, “Matlab/Spice & Electro-Thermal modeling for the Smart Photovoltaic System”, master thesis at IMEC Belgium, pp. 14-20, Dec 2010.

[12] A. Baltzois, “Life-time power efficiency improvement of photovoltaic solar panel systems: analysis and modeling of DC-DC converters”, master thesis at IMEC Belgium, June 2010.